PATENTS
112008-0027C1

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11/16/99 jc544 U.S. PTO

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In Re The Application of:
John Abedor, et al

Serial No.: NOT ASSIGNED

Filed: Nov. 16, 1999

Parent:
Serial No.: 08/740,637
Filed: October 31, 1996

Examiner: Nguyen, John

Art Unit: 2513

For: ESTIMATING TAPE PACK RADIUS USING A KALMAN FILTER

Cesari and McKenna, LLP
30 Rowes Wharf
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Naovember 16, 1999

"Express Mail" Mailing-Label Number: EL 0246 95069 US

Honorable Assistant Commissioner for Patents
Washington, D.C. 20231

Sir:

TRANSMITTAL LETTER

Transmitted for filing in the United States Patent and Trademark Office are the following:

1. Continuation Application
   22 pages including 12 claims and an Abstract
   4 sheets of drawings
2. Copy of Declaration and Power of Attorney from Parent Aplication
3. Preliminary Amendment
4. Fee Transmittal
5. Utility Transmittal

6. Check in the Amount of $ 838.00
7. Petition for Extension of Time for two months (2) for filing in the Parent Application
8. Check in the amount of $ 380.00 for the Extension of Time.
9. Postcard

Please charge any additional fee occasioned by this paper to our Deposit Account No. 03-1237.

Respectfully submitted,

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Please type a plus sign (+) Inside this box [+]

UTILITY PATENT APPLICATION TRANSMITTAL (Only for new nonprovisional applications under 37 C F R. § 1 53(b))	
Attorney Docket No.	112008-0027C1
First Inventor or Application Identifier	John Abedor, et al
Title	ESTIMATING TAPE PACK RADIUS USING A KALMAN FILTER
Express Mail Label No.	EL024695069US

APPLICATION ELEMENTS
See MPEP chapter 600 concerning utility application contents

ADDRESS TO: Assistant Commissioner for Patents
Box Patent Application
Washington, DC 20231

1. [X] *Fee Transmittal Form (e.g., PTO/SB/17)
(*Submit an original and a duplicate for fee processing*)
2. [X] Specification [*Total Pages* 22]
(*preferred arrangement set forth below*)
   - Descriptive title of the Invention
   - Cross References to Related Applications
   - Statement Regarding Fed sponsored R & D
   - Reference to Microfiche Appendix
   - Background of the Invention
   - Brief Summary of the Invention
   - Brief Description of the Drawings (*if filed*)
   - Detailed Description
   - Claim(s)
   - Abstract of the Disclosure
3. [X] Drawing(s) [*Total Sheets* 4]
4. Oath or Declaration [*Total Pages*]
   a [ ] Newly executed (original copy)
   b. [X] Copy from a prior application (37 C F R § 1 63(d))
   (*for continuation/divisional with Box 17 completed*)
   [Note Box 5 below]
   [ ] DELETION OF INVENTOR(S)
   Signed statement attached deleting inventor(s) named in the prior application, see 37 C.F.R. §§ 1 63(d)(2) and 1 33(b)
5. [X] Incorporation By Reference (*useable if Box 4b is checked*)
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered to be part of the disclosure of the accompanying application and is hereby incorporated by reference therein
6. [ ] Microfiche Computer Program (*Appendix*)
7. Nucleotide and/or Amino Acid Sequence Sequence Submission
((*if applicable, all necessary*)
   a. [ ] Computer Readable Copy
   b. [ ] Paper Copy (Identical to computer copy)
   c. [ ] Statement verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

8. [ ] Assignment Papers (cover sheet & document(s))
9. [ ] 37 C.F.R.§3.73(b) Statement (*when there is an assignee*) [X] Power of Attorney
10. [ ] English Translation Document (*if applicable*)
11. [ ] Information Disclosure Statement (IDS)/PTO-1449 [ ] Copies of IDS Citations
12. [X] Preliminary Amendment
13. [X] Return Receipt Postcard (MPEP 503) (*Should be specifically itemized*)
14. [ ] *Small Entity Statement(s) ((*PTO/SB/09-12*) [ ] Statement filed in prior application, Status still proper and desired
15. [ ] Certified Copy of Priority Document(s) (*if foreign priority is claimed*)
16 [ ] Other:

*NOTE FOR ITEMS 1 & 14: IN ORDER TO BE ENTITLED TO PAY SMALL ENTITY FEES, A SMALL ENTITY STATEMENT IS REQUIRED (37 C. F. R. §1.27), EXCEPT IF ONE FILED IN A PRIOR APPLICATION IS RELIED UPON (37 C. F. R § 1 28)

17. If a CONTINUING APPLICATION, *check appropriate box and supply the requisite information below and in a preliminary amendment*:
[X] Continuation [ ] Divisional [ ] Continuation-in-part (CIP) of prior application No.: 8/740,637
Prior application Information: *Examiner* John Nguyen *Group/Art Unit*: 2513

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PRELIMINARY AMENDMENT

IN THE SPECIFICATION

At Page 2 Line 1 insert before "FIELD OF THE INVENTION", the following:

--RELATED APPLICATIONS

This Application is a Continuation of Application No. 08/740,637 filed October 31, 1996, all disclosures of which are incorporated herein by reference. --

REMARKS

It is believed that no charges are due as a result of filing this amendment.

Please charge any additional fee occasioned by this paper to our Deposit Account No. 03-1237.

Respectfully submitted,

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PATENT
112008-0027

JC544 U.S. PTO
11/16/99

UNITED STATES PATENT APPLICATION

of

John Abedor

and

Kurt Hallamasek

for

SYSTEM FOR ESTIMATING TAPE PACK RADIUS USING A KALMAN FILTER

FIELD OF THE INVENTION

The invention relates to tape systems, and in particular, to systems for determining the tape pack radius of supply and/or take-up reels.

BACKGROUND OF THE INVENTION

Tape systems generally have two reels for storing tape, namely, a supply reel and a take-up reel, a capstan for moving the tape from reel to reel and tension arms for regulating the tape tension. High-performance tape systems also include servo systems, which regulate tape position and velocity. The servo systems rely on estimates of the tape pack radii to determine how to control the rotational speeds of the reels to achieve the desired tape velocity and position. The more accurate the estimates, the more precisely the servo system can control the movement of the tape.

Good estimates of the tape pack radii are fundamentally important in controlling all aspects of the system operations. For example, good estimates are important in determining from which reel to draw the tape to wrap around a scanner. An inaccurate estimate could result in an over-rotation of the selected reel. Further, good estimates are important to determining when to decelerate a high-speed rewind operation, again to avoid over-rotation of one of the reels that may result in the breaking of the tape of the detatchment of the tape from the reel. Also, good estimates are important to determine if there is sufficient tape available on the supply reel to complete a record operation. Inaccurate estimates of the reel pack radii can result in incomplete record operations, if the system sufficiently under estimates the tape position.

In prior known systems the tape pack radius is calculated from measurements of the angular positions of the reels and the capstan. The position measurements are made by, for example, optical encoders that count the number of slots that pass between a photo detector and a light source as the reel rotates. The calculations produce results that are at best as accurate as the position measurements, which tend to be "noisy." With optical encoders, for example, the measurement noise is due in large part to quantitization errors. At slow speeds these systems tend to produce relatively inaccurate results because the position measurements are comparable to the quantitization errors.

Certain prior systems have processed the noisy measurement using low-pass filters, in order to smooth them. However, this approach has two significant problems. First, the signals produced by these filters always lag behind the true tape pack radii, or in other words, the estimates are biased. Second, these filters are slow to converge. Moreover, there is an intrinsic tradeoff - the more the filter smooths the output signals, i.e., the estimates of the tape pack radii, the more lag is introduced into the system and the slower the convergence.

SUMMARY OF INVENTION

The invention is a tape system that uses a Kalman filter to produce both an estimate of the tape pack radius and an estimate of the associated estimation error variance. The Kalman filter produces the estimates based on current and prior angular estimation position measurements of the reel, capstan, and tension arm, and the prior estimates of both the tape pack radius and the estimation error variance. The filter gain is based on the prior estimation error variance and a calculated measurement

error variance, which is a function of the current and prior measurements. Preferably, the system uses two Kalman filters, one to produce the estimates for the supply reel and one or produce the estimates for the take-up reel.

More specifically, the Kalman filter includes a model of the dynamics of the system that it uses to predict what the tape pack radius and estimation error variance will be at the time of a new measurement. The Kalman filter then updates the estimate of the tape pack radius when a new measurement is made, based on this predicted radius and a correction factor that is the weighted difference between a "measured" reel pack radius (calculated from reel, capstan, and tension arm measurements) and the predicted radius. This weight, which is Kalman filter gain, is a function of the estimation error variance and a measurement noise, or error variance.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the invention may be better understood by referring to the following description in conjunction with the accompanying drawings, in which:

Fig. 1 is a functional block diagram of a system constructed in accordance with the invention;

Fig. 2 is a flowchart of the operations of the system of Fig. 1; and

Fig. 3 is a flowchart of the operations of the system of Fig. 1 when the system is operating in a coasting mode.

DETAILED DESCRIPTION

1. The System

Referring to Fig. 1, a tape system includes a capstan 14 that transfers tape 12 between a supply reel 10 and a take-up reel 16. When the reels rotate clockwise, as depicted by the arrows, tape is wound off of the supply reel and onto the take-up reel and, thus, the tape pack radius of the supply reel decreases as the tape pack radius of the take-up reel increases.

Angular position transducers 21-25, which may be, for example, optical encoders, are attached to the shafts (not shown) of the capstan 14, the two reels 10 and 16, and the tension arms 18 and 20. The transducers operate in a conventional manner to measure, respectively, the angular positions of the capstan, the reels and the tension arms.

A supply Kalman filter 26a receives measurements from transducers 21, 22 and 24, and a take-up Kalman filter 26b receives measurements from transducers 23, 22, and 25. These measurements are used by the filters to produce estimates of the tape pack radii and estimates of associated estimation error variances, which provide a confidence interval around each tape pack radius estimate. The operations of the filters 26a and 26b are discussed in more detail with reference to Fig. 2 below. Also as discussed in more detail below, the estimates produced by the filters are used by a servo system 28 that controls the motion of and the tension in the tape 12, and by a tape length estimator 30 that determines how much tape is available for a record operation.

The tape system includes other well-known elements such as additional tape guides, scanners, longitudinal heads, and so forth, none of which are shown in the

drawing. As long as these elements are fixed in position so that they do not cause the tape path to vary, their presence is immaterial to the operations of the Kalman filters 26a and 26b. The effects on the operations of the filters of a change in the tape path length, for example, by means of movable guides, is discussed below with reference to Fig. 4.

2. The Theory

We can look at the system as two subsystems, namely, a supply subsystem that includes the supply reel 10, the supply tension arm 18 and the capstan 14, and a take-up subsystem that includes the take-up reel 16, the take-up tension arm 20 and the capstan 14. The two subsystems have identical theories of operation, and we discuss herein the theory of operation of the take-up subsystem.

Let us consider the case when position measurements are made at regular short intervals of, for example, 20 milliseconds. If the tape is moving, the length of tape that is wound onto the take-up reel 16 must travel past the capstan 14, and we can state that, to a high degree of accuracy,

$$r_r\Delta\theta_r + \mu_a\Delta\theta_a - r_c\Delta\theta_c = 0$$

where r_r is the radius of the take-up reel tape pack, $\Delta\theta_r$ is the change in angular position of the take-up reel 16 from the previous sample time to the current sample time, $\Delta\theta_c$ is the change in angular position of the capstan, μ_a is a gain determined by the geometry of the tape path and the nominal position of the take-up tension arm 20, and $\Delta\theta_a$ is the change in angular position of the arm. The radius of the take-up reel is thus:

$$r_r = \frac{r_c \Delta\theta_c - \mu_a \Delta\theta_a}{\Delta\theta_r} \qquad \text{eqn. 1}$$

If the tape is moving relatively slowly the "deltas," that is, the changes in the angular positions are comparable in magnitude to the position measurement errors. If the system relies solely on these measurements to determine tape pack radius and ignores both past measurements and the dynamics of the system, errors in position measurements translate directly to inaccuracies in the determination of the tape pack radius. The prior systems discussed above in the Background section all suffer from this problem.

Our system circumvents those problems through the use of a Kalman filter, which has as an input signal a "measured" radius r_m, that is calculated using equation 10. The Kalman filter incorporates a model of how the tape pack radius changes as a function of reel position to predict an estimated tape pack radius. The filter then uses the measured radius to correct this prediction. The derivation of the predictive model is considered here.

Consider the tape pack as a hollow, circular cylindrical mass with width "w", and a uniform density "*d*," i.e. mass per unit volume, where *d* is the density of the tape itself. If a length of tape " *l* " units long, with width w and thickness "δ " is wound onto the reel, the mass of the tape pack increases by the mass of that length of tape, and the radius of the tape pack increases accordingly.

The mass of the tape pack before the length of tape is wound on is:

$$dw\pi r_1^2 - dw\pi r_0^2$$

where r_1 is the outer radius of the tape pack and r_0 is the inner radius of the tape pack, i.e., the radius of the reel hub. Suppose that the radius of the pack increases to r_2

when the length of tape is wound onto the tape pack. The mass of the tape pack thus increases to:

$$dw\pi r_2^2 - dw\pi r_0^2 \qquad \text{eqn. 2}$$

The increase in the mass of the tape pack due to the tape being wound onto the reel is $dwl\delta$, which is the mass of the additional tape, hence:

$$dw\pi r_2^2 - dw\pi r_0^2 = dw\pi r_1^2 - dw\pi r_0^2 + dwl\delta.$$

Solving for r_2 we have:

$$r_2 = \left(r_1^2 + \frac{1}{\pi}\ell\delta\right)^{\frac{1}{2}} \qquad \text{eqn. 3}$$

Given an initial reel radius r, this equation enables us to approximately predict what the radius will be after we wind on the additional tape of length l. What we are really interested in, however, is an equation that allows us to predict what the radius will be given an initial reel radius and an amount by which the reel rotates. If the reel rotates in the clockwise direction by a small amount $\Delta\theta_r$ and the reel radius is initially r, a length of tape equal to $r\Delta\theta_r$ is wound onto the tape pack and the tape pack radius increases by Δr, which according to eqn. 3 satisfies:

$$r + \Delta r = \left(r^2 + \frac{1}{\pi} r\Delta\theta_r\delta\right)^{\frac{1}{2}}$$

$$= r\left(1 + \frac{\Delta\theta_r\delta}{\pi r}\right)^{\frac{1}{2}}$$

$$\approx r\left(1 + \frac{\Delta\theta_r\delta}{2\pi r}\right),$$

hence

$$\Delta r = \frac{\Delta\theta_r \delta}{2\pi r}$$

and, in the limit,

$$\dot{r} = \frac{\delta}{2\pi}\dot{\theta}_r \qquad \text{eqn. 4}$$

The desired predictive equation is the integral of eqn. 4, from an initial time t_0 to the time t_f for which the prediction is required:

$$r(t_f) - r(t_0) = \frac{\delta}{2\pi}\left[\theta_r\left(t_f\right) - \theta_r(t_0)\right]$$

where $r(t_j)$ is the tape pack radius at time t_j, and $\theta_r(t_i)$ is the angular position of the take-up reel at time t_i. Thus:

$$r(t_f) = r(t_0) + \frac{\delta}{2\pi}\left[\theta_r(t_n) - \theta_r(t_0)\right] \qquad \text{eqn. 5}$$

Inaccuracies in this model are accounted for in the Kalman filter by an estimate of "noise" applied to the system - that is, by quantifying as applied noise essentially unmeasurable attributes of the system dynamics. The applied noise is one of the factors that is used in determining the Kalman filter gain, k, as discussed below with reference to Figs. 2 and 3.

To determine the filter gain, the system also requires an estimate of the measurement noise, or error, variance. The system implicitly assumes that the errors in the various position measurements can be represented by independent, zero-mean random variables ε_i, which each have "small" variances. We know that for a smooth (differentiable) function g that maps "n" real numbers to one real number, we have:

$$\text{var}(g(x_1+\varepsilon_1,\ldots,x_n+\varepsilon_n)) \approx$$

$$\left(\left(\frac{\partial g}{\partial x_1}(x)\right)^2 \operatorname{var}(\varepsilon_1) + \ldots + \left(\frac{\partial g}{\partial x_n}(x)\right)^2 \operatorname{var}(\varepsilon_n) \right.$$

From this relation we obtain the approximate measurement noise variance. Based on equation 1, we define the function g as:

$$g(\theta_c,\ \theta_{c-}, \theta_a,\ \theta_{a-},\ \theta_r,\ \theta_{r-}) = \frac{r_c(\theta_c - \theta_{c-}) - \mu_a(\theta_a - \theta_{a\_})}{\theta_r - \theta_{r\_}}$$

where θ_c is the position of the capstan at the current sample time, $\theta_{c\_}$ is the position of the capstan at the previous sample time, θ_a and θ_{a-} are the positions of the tension arm at the current and previous sample times, and θ_r and θ_{r-} are the positions of the take-up reel at the current and previous sample times. If these quantities are perturbed, respectively, by independent, zero-mean random variables ε_c, ε_a and ε_r, the approximate measurement error variance σ_m^2 is:

$$\sigma_m^2 = \frac{2}{\theta_r - \theta_{r\_}}\left[r_c^2 \operatorname{var}(\varepsilon_c) + \mu_a^2 \operatorname{var}(\varepsilon_a) + g(\theta_c, \theta_c, \theta_a, \theta_{a\_}, \theta_r, \theta_{r-})^2 \operatorname{var}(\varepsilon_r)\right] \quad \text{eqn. 6}$$

The variances var(ε_c), var (ε_a) and var (ε_r) are computed by assuming that the quantitization error is a random variable with zero mean that is uniformly distributed over an interval of size $\frac{2\pi}{N}$ radians, where N is the number of encoder counts per revolution.

The system ignores measurements that it determines to be unreasonable. As discussed below with reference to Fig. 3, the system considers a measurement to be unreasonable if the associated measurement error variance, σ_m^2, is greater than the maximum variance σ_{max}^2, or if the three-sigma measurement interval around the

calculated measured radius r_m, as determined by the measurement model, is not at least partially included within the interval from the minimum tape pack radius, r_{min}, to the maximum tape pack radius, r_{max}. Ignoring the unreasonable measurements greatly improves the robustness of the Kalman filter to capstan slip.

The Kalman filters use equations 1 and 6 to produce estimates of the tape pack radii and the associated measurement error variances, respectively, as discussed below.

3. System Operation

Referring now to Figs. 1 and 2, when a tape, for example, a cassette tape, that is wound on the supply and take-up reels 10 and 16, is loaded into the system, the system has no indication of the tape pack radii. Accordingly, the tape pack radii processor 26 in step 300 must initialize the Kalman filter with (1) an initial tape pack radius estimate, (2) an initial estimation error variance and (3) initial position measurements of the capstan, the tension arm, and the reel, that is, θ_c, θ_a, and θ_r, where θ_r, is the angular position of the tape reel under consideration, for example, the take-up reel. We discuss below the operations of the system in determining the tape pack radius of the take-up reel 16. The system performs the same operations to produce estimates of the tape pack radius of the supply reel 10 and the associated estimation error variance.

The processor 26 uses as the initial estimate of the tape pack radius:

$$\hat{r}^- = \frac{r_{max} + r_{min}}{2}$$

which is the radius when one-half of the tape is wound on the reel, and uses as an estimate of the initial estimation error variance:

$$v^{-} = \frac{(r_{\max} - r_{\min})^2}{12}$$

which is the variance of a uniformly distributed variable over the interval r_{min} to r_{max}. This initial estimate of the error variance is relatively large and indicates that the initial estimate of the tape pack radius is very likely to be inaccurate.

The processor 26 takes a next set of position measurements θ_c, θ_a, and θ_r, and calculates $\Delta\theta_c$, $\Delta\theta_a$ and $\Delta\theta_r$, using the initial set of measurements as the measurements of the previous sample time, namely, θ_{c-}, θ_{a-} and θ_{r-} (step 302).

Using these delta values, the processor, in step 304, calculates a "measured" radius, r_m:

$$r_m = \frac{r_c \Delta\theta_c - \mu_a \Delta\theta_a}{\Delta\theta_r}$$

The processor, in step 306, next determines if the calculated radius falls outside of the interval of possible radii, namely, the interval r_{min} to r_{max}. If so, the processor sets the calculated r_m to r_{min} if r_m is less than r_{min}, or to r_{max} if r_m is greater than r_{max} (step 308).

The system then in step 310 calculates a measurement error variance σ_m^2, using the measured $\Delta\theta_r$ and the calculated radius r_m:

$$\sigma_m^2 = \frac{2}{\Delta\theta_r}\left[r_c^2 \operatorname{var}(\varepsilon_c) + \mu_a^2 \operatorname{var}(\varepsilon_a) + r_m^2 \operatorname{var}(\varepsilon_r)\right]$$

If the calculated measurement error variance is larger than the maximum estimation error variance, which is determined by equation 7, the processor determines that the angular position measurements are unreasonable (steps 312, 314).

Assuming the calculated measurement error variance is not greater than the maximum estimation error variance, the processor further tests the reasonableness of the measurements by determining if at least a portion of the three sigma interval around r_m is within the interval of r_{min} to r_{max} (step 316). If so, the processor determines that the measurements are reasonable, and uses the calculated radius r_m and measurement error variance σ_m^2 in the Kalman filter to determine estimates of the tape pack radius and the estimation error variance. Otherwise, the system determines that the measurements are unreasonable and, as discussed below, uses predicted values for the estimates.

If the measurements are reasonable, the processor, in step 318, calculates the Kalman filter gain, k, as:

$$k = \frac{v^-}{v^- + \sigma_m^{\ 2}}$$

where v^- is the estimation error variance extrapolated from the previous sample time. The processor next, in step 320, updates the estimate of the tape pack radius as:

$$\hat{r}^+ = \hat{r}^- + k(r_m - \hat{r}^-)$$

and updates the estimation error variance as:

$$v^+ = \frac{1-k}{v^-}\ .$$

These updated estimates are the output signals of the filter. The servo controller 28 and a tape length counter (not shown) then use these estimates to determine how to control the tape system, as discussed below. Next, the tape pack radius and estimation error variance are propagated to the next sample time. The radius estimate is propagated according to the predictive equation:

$$\hat{r}^- = \hat{r}^+ + \frac{\delta}{2\pi}\Delta\theta_r,$$

which comes from equation 5, and the estimation error variance is propagated according to the equation:

$$v^- = v^+ + \sigma_v^2,$$

where σ_v^2 is a constant that represents the inaccuracies of, or the noise applied to, the predictive model.

The servo controller 28 uses the estimated tape pack radii in conventional feedback and feed-forward loops that control the rotational speeds of the reels and move the tape at a desired velocity. The tape length estimator 30, which determines how much tape is available for record operations, uses as a lower bound for the tape pack radii:

$$\hat{r}^+ - 3\sigma.$$

This is a conservative estimate, which prevents the tape length estimator from over estimating the length of the tape available for a given record operation.

If the processor 26 determines that the measurements are unreasonable, it does not update the filter gain. Further, it does not calculate the updated estimates. Instead, it predicts what the estimates should be based solely on the previous

estimates. The processor, in step 315, sets $\hat{r}^+ = \hat{r}^-$ and $v^+ = v^-$ and predicts an estimate of the tape pack radius $\hat{r}^-$ as:

$$\hat{r}^- = \hat{r}^+ + \frac{\delta}{2\pi}\Delta\theta_r$$

and the error variance v^- as :

$$v^- = v^+ + \sigma_v^2$$

The processor then sets the measured values θ_c, θ_a and θ_r as the prior values θ_{c-}, θ_{a-}, and θ_{r-}, respectively, and repeats steps 302-320 to calculate updated estimates for the next sample time.

The system continues to determine and, as appropriate, predict estimates for the tape pack radii and the associated error variances as long as estimates are required, that is, as long as the reels continue to rotate.

Referring now to Fig. 4, the processor operates in a "coasting" mode when the tape path length is altered by anything but the tension arm. For example, the system operates in the coasting mode when the tape is being unwound from one reel and wrapped around the scanner (not shown). The system also operates in a coasting mode when the tape is being withdrawn from the scanner. These operations, which significantly change the length of the tape path, are not included in the underlying assumptions upon which the measurement model in the Kalman filter is based. Accordingly, the measured radius r_m produced by that model cannot be used to determine the estimates of the tape pack radius and the error variance when the path length is so altered. The estimates are instead produced using the predictive model.

The system thus extrapolates from the current estimates of tape pack radius and estimation error variance to the next sample time by taking a next set of position measurements (step 402), determining $\Delta\theta_c$, $\Delta\theta_a$ and $\Delta\theta_r$ (step 404) and estimating the tape pack radius by:

$$\hat{r}^- = \hat{r}^+ + \frac{\delta}{2\pi}\Delta\theta_r$$

and the error variance by

$$v^- = v^+ + \sigma_v^2$$

where σ_v^2 is a constant that represents the inaccuracies in the predictive model (step 406). It next, in step 408, sets θ_{c-}, θ_{a-} and θ_{r-} equal to the measured values and $\hat{r}^+ = \hat{r}^-$ and $v^+ = v^-$, and at the next sample time again begins the process of predicting the estimates. The system thus returns to step 402.

The processor continues operating in the coasting mode while the system is varying the tape path length. Once the tape path length is held constant, the processor again utilizes the filter gain, and operates as discussed above with reference to Fig. 3.

Generally, the system operates in the coasting mode for only a small number of consecutive sample times. By predicting new radii and estimation error variance values during the coasting operations, the processor can determine at the end of these operations reliable updated estimates for the tape pack radii and error variance, as well as a reliable filter gain, which is based in part on these estimates.

While the measurement model could be revised to include the system operations in which the path length is varied, it is not necessary since the time the system spends

so little time performing these operations. Thus, the trade off of increased complexity in the model for more accuracy during these limited path-varying operations seems unwarranted. Further, since the estimates produced by the Kalman filter converge rapidly, the accuracy of the system is only minimally reduced by not including in the model the path-varying operations.

The foregoing description has been limited to a specific embodiment of this invention. It will be apparent, however, that variations and modifications may be made to the invention, with the attainment of some or all of its advantages. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the invention.

What is claimed is:

CLAIMS

1 . A system for measuring tape pack radii, comprising:

a tape supply reel, said tape supply reel rotating as a tape leaves said tape supply reel during a tape transfer process;

a tape take-up reel for receiving tape from said tape supply reel, said tape take-up reel rotating as it receives said tape during said tape transfer process;

an at least one encoder responsive to movement of said tape;

a first angular position transducer to measure an angular position of said tape supply reel;

a second angular position transducer to measure an angular position of said tape take-up reel;

a third transducer responsive to said at least one encoder;

a Kalman filter, responsive to one or both of an angular position measurement by said first angular position transducer and an angular position measurement by said second angular position transducer and also responsive to an angular position measurement by said third angular position transducer, to calculate an updated estimate of one or both of a supply radius of a tape pack on said tape supply reel and a take-up radius of a tape pack on said tape take-up reel;

a servo-controller, responsive to one or both of said supply radius and said take-up radius, to control rotation of said tape supply reel and said tape take-up reel.

2. The apparatus as in claim 1, wherein said Kalman filter further comprises:

a supply Kalman filter responsive to said first angular position transducer and said third angular position transducer;

a take-up Kalman filter responsive to said second angular position transducer and said third angular position transducer.

3. The apparatus as in claim 1 wherein said at least one encoder further comprises:

a first encoder responsive to an angular position of a supply reel tension arm;

a second encoder responsive to an angular position of a take-up reel tension arm.

4. The apparatus as in claim 1, further comprising:

a capstan, said tape contacting said capstan and said capstan rotating as said tape transfers from said tape supply reel to said tape take-up reel.

5. The apparatus as in claim 3 wherein said at least one encoder further comprises:

a third encoder responsive to an angular position of a capstan.

6. The apparatus as in claim 1 further comprising:

a tape length estimator responsive to said Kalman filter to determine the amount of tape available for a record operation.

7. A system for measuring a length of tape available for a record operation, comprising:

a tape supply reel, said tape supply reel rotating as a tape leaves said tape supply reel during a tape transfer process;

a tape take-up reel for receiving tape from said tape supply reel, said tape take-up reel rotating as it receives said tape during said tape transfer process;

an at least one encoder responsive to movement of said tape;

a first angular position transducer to measure an angular position of said tape supply reel;

a second angular position transducer to measure an angular position of said tape take-up reel;

a third transducer responsive to said at least one encoder;

a Kalman filter, responsive to one or both of an angular position measurement by said first angular position transducer and an angular position measurement by said second angular position transducer and also responsive to an angular position measurement by

said third angular position transducer, to calculate said length of tape available for a record operation.

8. A method for estimating a radius of a tape on a supply reel and on a take-up reel, comprising:

measuring a first angular position of a tape supply reel;

measuring a second angular position of a tape take-up reel;

measuring a third angular position responsive to movement of a tape; and,

estimating by a Kalman filter a radius of a tape pack on said supply reel and a radius of a tape pack on said take-up reel, in response to said first angular position of said tape supply reel, said second angular position of said tape take up reel, and said third angular position responsive to movement of said tape.

9. The method as in claim 8 wherein said estimating step by said Kalman filter further comprises:

responding to an initial estimate of said radius of a tape pack on said supply reel;

responding to an initial estimate of a radius of tape pack on said take-up reel; and,

responding to said first angular position measurement, said second angular position measurement, and said third angular position measurement to compute said radius of said tape pack on said supply reel and said radius of said tape pack on said take-up reel.

10. The method of claim 8 further comprising:

making said first angular measurement at a first regular time interval;

making said second angular measurement at a second regular time interval;

making said third angular measurement at a third regular time interval.

11. The method of claim 10 further comprising:

choosing said first regular time interval, said second regular time interval and said third regular time interval each to be approximately 20 milliseconds.

12. . A method for estimating a length of tape available for a record operation, comprising:

measuring a first angular position of a tape supply reel;

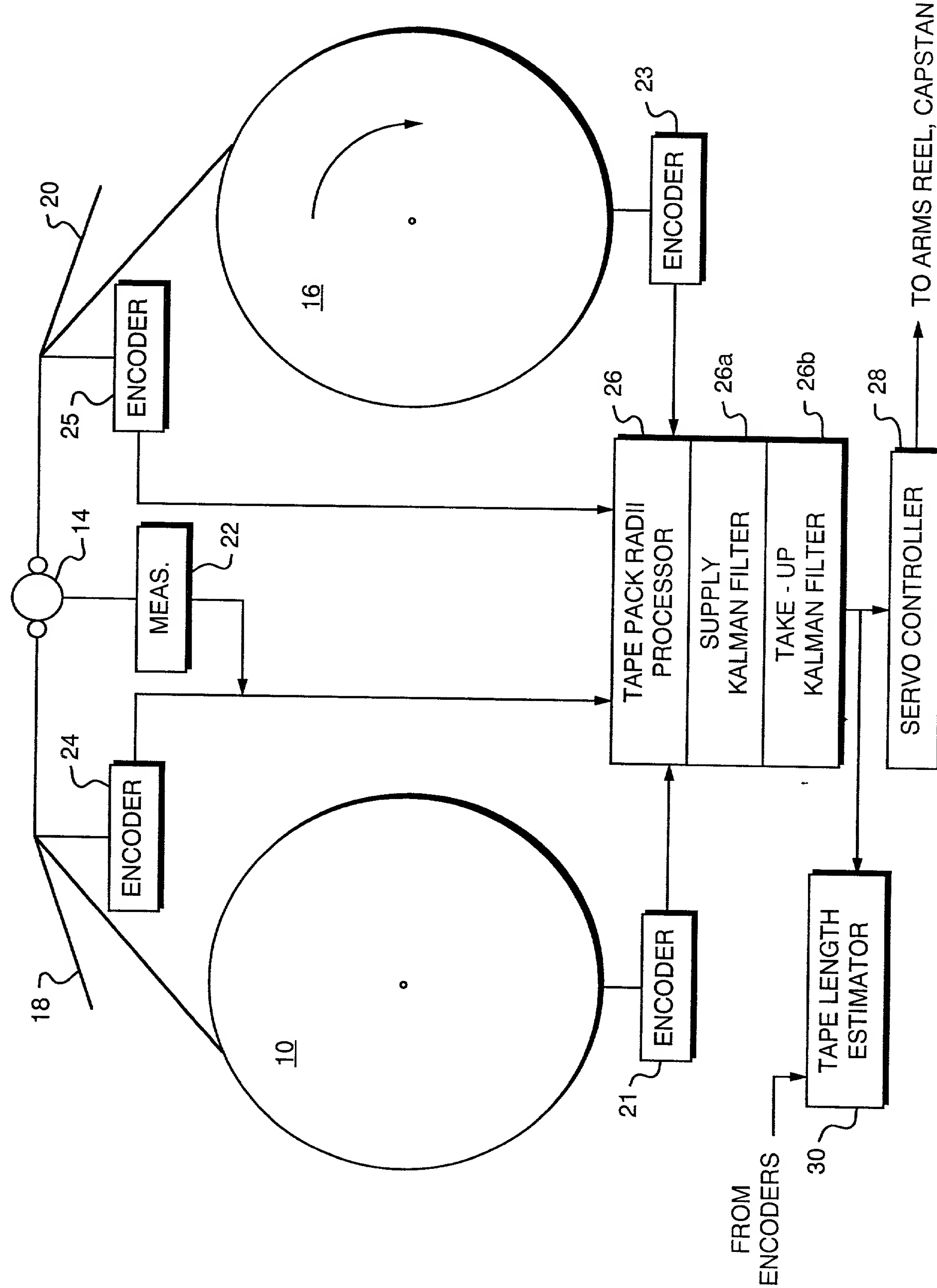
measuring a second angular position of a tape take-up reel;

measuring a third angular position responsive to movement of a tape; and,

estimating by a Kalman filter said length of tape available for a record operation, in response to said first angular position of said tape supply reel, said second angular position of said tape take up reel, and said third angular position responsive to movement of said tape.

ABSTRACT

A system for measuring a length of tape available for a record operation has both a tape supply reel which rotates as a tape leaves the supply reel during a tape transfer process, and a tape take-up reel which receives tape from the supply reel, and the tape take-up reel also rotates as it receives the tape during the tape transfer process. There are provided an encoder responsive to movement of the tape, a first angular position transducer to measure an angular position of the tape supply reel, a second angular position transducer to measure an angular position of the tape take-up reel, and a third transducer responsive to the encoder. A Kalman filter, responsive to an angular position measurement by the first angular position transducer, the second angular position transducer, and also the third angular position transducer, calculates the length of tape available for a record operation. The Kalman filter also calculates the radius of the tape pack on the supply reel, and the radius of the tape pack on the take-up reel.


10
16
18
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14
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24
25
21
23
ENCODER
ENCODER
ENCODER
ENCODER
MEAS.
26
26a
26b
TAPE PACK RADII PROCESSOR
SUPPLY KALMAN FILTER
TAKE - UP KALMAN FILTER
28
SERVO CONTROLLER
TO ARMS REEL, CAPSTAN
30
TAPE LENGTH ESTIMATOR
FROM ENCODERS

FIG. 1

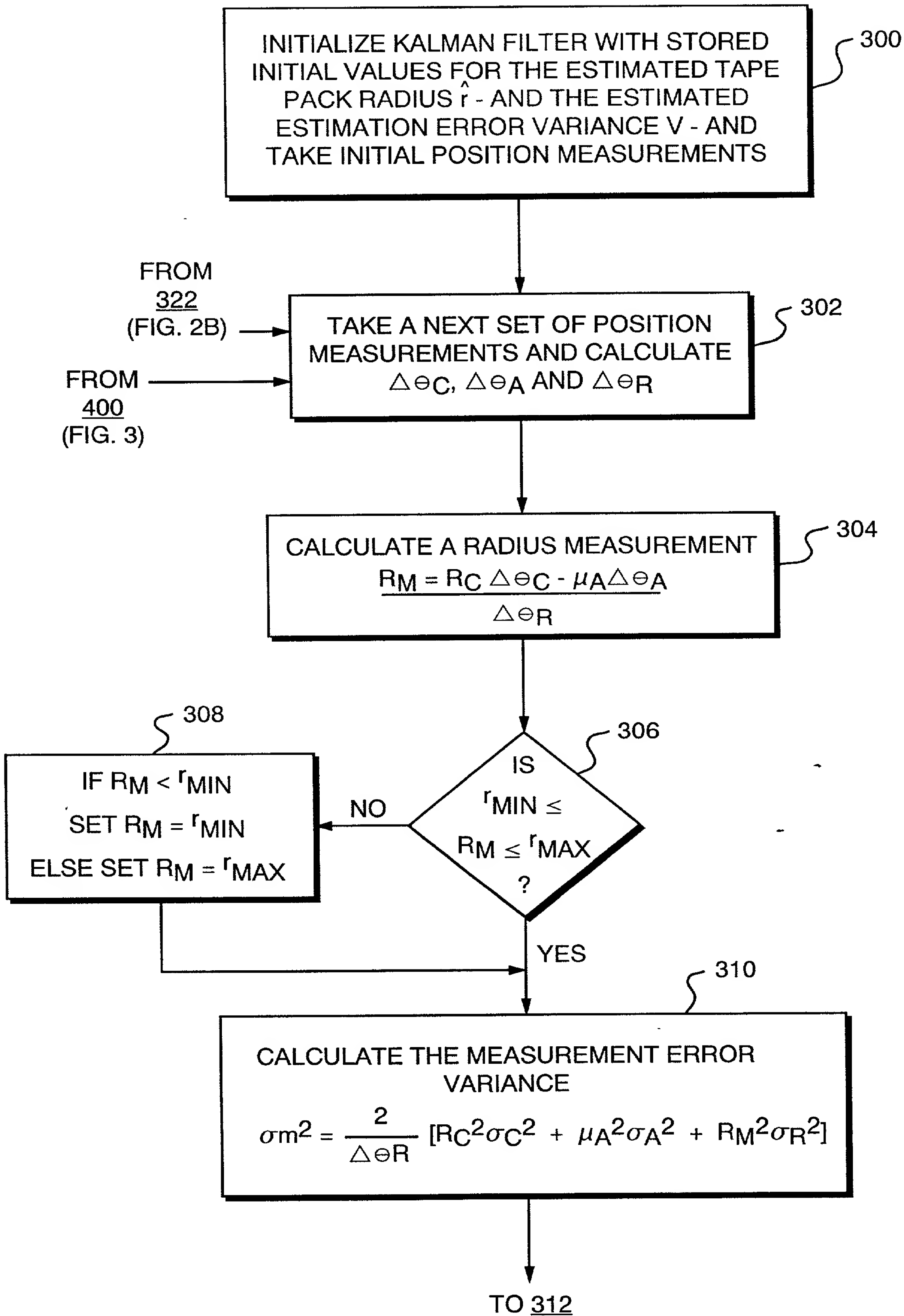
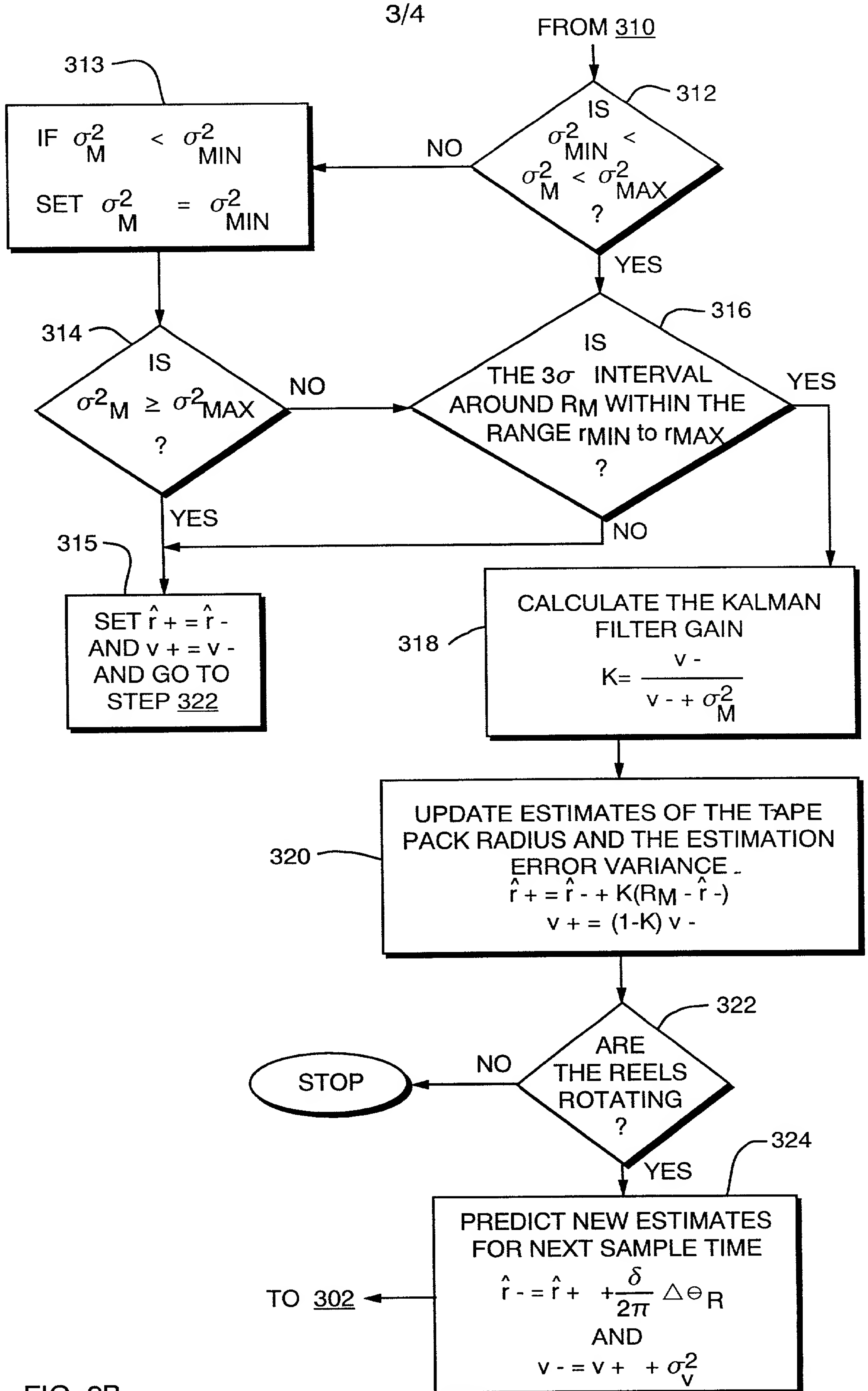

INITIALIZE KALMAN FILTER WITH STORED INITIAL VALUES FOR THE ESTIMATED TAPE PACK RADIUS $\hat{r}$ - AND THE ESTIMATED ESTIMATION ERROR VARIANCE V - AND TAKE INITIAL POSITION MEASUREMENTS
300
FROM 322 (FIG. 2B)
FROM 400 (FIG. 3)
TAKE A NEXT SET OF POSITION MEASUREMENTS AND CALCULATE $\Delta\theta_C$, $\Delta\theta_A$ AND $\Delta\theta_R$
302
CALCULATE A RADIUS MEASUREMENT
$R_M = \dfrac{R_C \Delta\theta_C - \mu_A \Delta\theta_A}{\Delta\theta_R}$
304
308
IF $R_M < r_{MIN}$
SET $R_M = r_{MIN}$
ELSE SET $R_M = r_{MAX}$
NO
IS $r_{MIN} \leq R_M \leq r_{MAX}$?
306
YES
310
CALCULATE THE MEASUREMENT ERROR VARIANCE
$\sigma m^2 = \dfrac{2}{\Delta\theta R} [R_C^2\sigma_C^2 + \mu_A^2\sigma_A^2 + R_M^2\sigma_R^2]$
TO 312

FIG. 2A



FROM 310
312
IS $\sigma^2_{MIN} < \sigma^2_M < \sigma^2_{MAX}$?
NO
313
IF $\sigma^2_M < \sigma^2_{MIN}$ SET $\sigma^2_M = \sigma^2_{MIN}$
YES
314
IS $\sigma^2_M \geq \sigma^2_{MAX}$?
NO
316
IS THE 3σ INTERVAL AROUND R_M WITHIN THE RANGE r_{MIN} to r_{MAX} ?
YES
YES
NO
315
SET $\hat{r}+ = \hat{r}-$ AND $v+ = v-$ AND GO TO STEP 322
318
CALCULATE THE KALMAN FILTER GAIN
$K = \frac{v-}{v- + \sigma^2_M}$
320
UPDATE ESTIMATES OF THE TAPE PACK RADIUS AND THE ESTIMATION ERROR VARIANCE
$\hat{r}+ = \hat{r}- + K(R_M - \hat{r}-)$
$v+ = (1-K)\,v-$
322
ARE THE REELS ROTATING ?
NO
STOP
YES
324
PREDICT NEW ESTIMATES FOR NEXT SAMPLE TIME
$\hat{r}- = \hat{r}+ + \frac{\delta}{2\pi}\Delta\Theta_R$
AND
$v- = v+ + \sigma^2_v$
TO 302

FIG. 2B

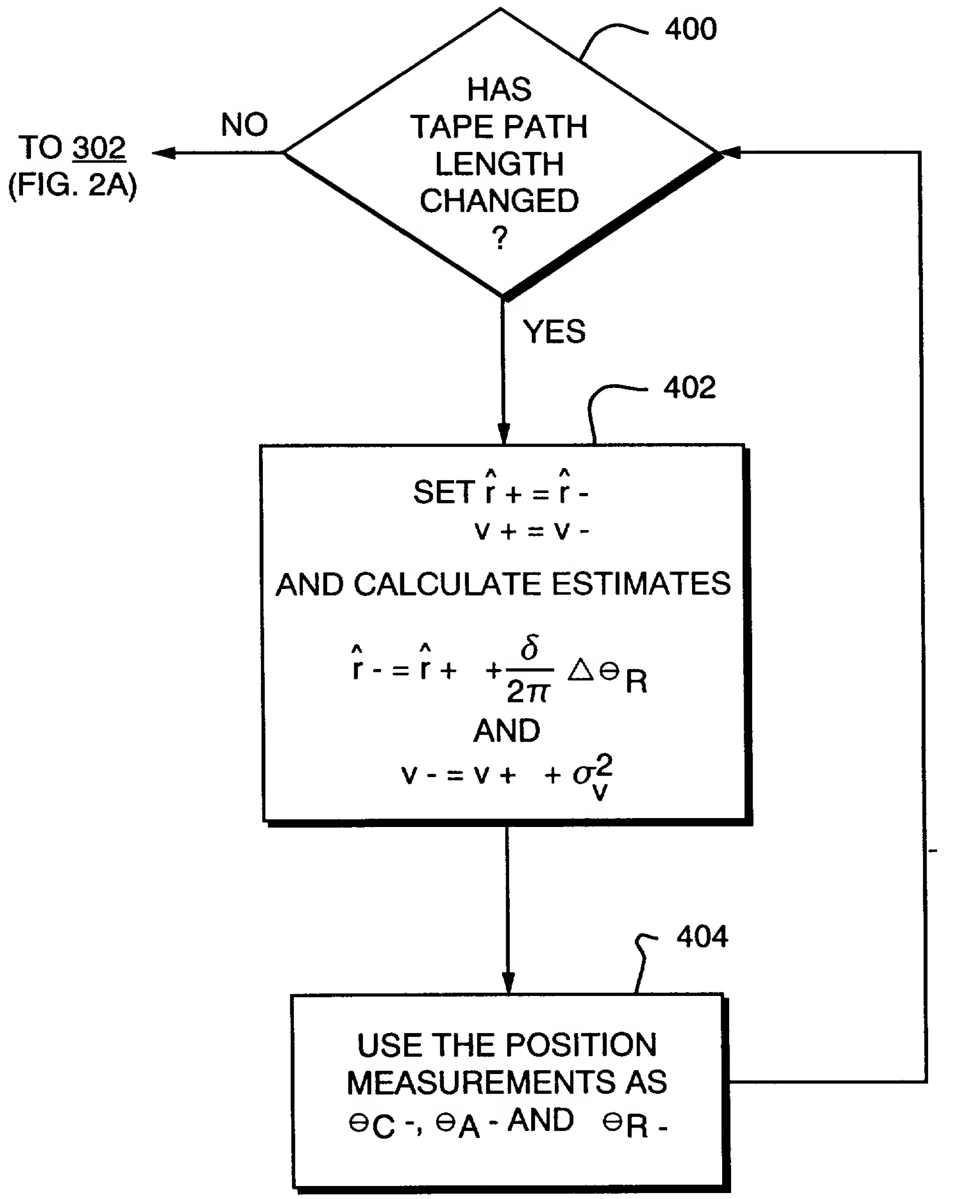

400
HAS TAPE PATH LENGTH CHANGED ?
NO
TO 302 (FIG. 2A)
YES
402
SET $\hat{r}+ = \hat{r}-$
$v+ = v-$
AND CALCULATE ESTIMATES
$\hat{r}- = \hat{r}+ + \frac{\delta}{2\pi} \Delta\Theta_R$
AND
$v- = v+ + \sigma_v^2$
404
USE THE POSITION MEASUREMENTS AS Θ_C-, Θ_A- AND Θ_R-

FIG. 3

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below-named inventor, I hereby declare that:

My residence, post-office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled SYSTEM FOR ESTIMATING TAPE PACK RADIUS USING A KALMAN FILTER, filed on October 31, 1996, and identified by U.S. Patent Application Serial No. 08/740,637.

I hereby state that I have reviewed and understand the contents of the above-identified application specification, including the claims, as amended by any amendment specifically referred to herein.

I acknowledge the duty to disclose all information known to me that is material to patentability in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code §119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed: None.

I hereby claim the benefit under Title 35, United States Code §120, of the United States Application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United State Code, §112, I acknowledge the duty to disclose all information that is material to patentability in accordance with Title 37, Code of Federal Regulations, §1.56, and which became available to me between the filing date of the prior application and the national or PCT international filing date of this application: None.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment or both under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint Michael E. Attaya, Reg. No. 31,731; Charles J. Barbas, Reg. No. 32,959; Joseph H. Born, Reg. No. 28,286; Robert A. Cesari, Reg. No. 18,381; Steven J. Frank, Reg. No. 33,497; William A. Loginov, Reg. No. 34,863; John F. McKenna, Reg. No. 20,912; Martin J. O'Donnell, Reg. No. 24,204; Thomas C. O'Konski, Reg. No. 26,320; Patrick J. O'Shea, Reg. No. 35,305; Michael R. Reinemann, Reg. No. 38,280; Rita M. Rooney, Reg. No. 30,585; Patricia A. Sheehan, Reg. No. 32,301; and Mark A. Superko, Reg. No. 34,027, Cesari and McKenna, LLP, 30 Rowes Wharf, Boston, Mass. 02110, jointly, and each of them severally, my attorneys and attorney, with full power of substitution, delegation and revocation, to prosecute this application, to make alterations and amendments therein, to receive the patent and to transact all business in the Patent and Trademark Office connected therewith. Please direct all telephone calls to Patricia A. Sheehan at (617) 951-2500. Please address all correspondence to Patricia A. Sheehan.

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